

Tidal breakup of the nucleus of Comet Shoemaker-Levy 9

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The breakup of Comet Shoemaker-Levy 9 is discussed both in the context of splitting as a cometary phenomenon, comparing this object with other split comets, and as an event with its own idiosyncrasies. The physical appearance of the comet is described, features diagnostic of the nature of tidal splitting are identified, and the implications for modelling the event are spelled out. Among the emphasized issues is the problem of secondary fragmentation, which documents the comet's continuing disintegration during 1992-94 and implies that in July 1992 the parent object split tidally near Jupiter into 1012, not 21, major fragments. Also addressed are the controversies involving models of a strengthless agglomerate versus a discrete cohesive mass and estimates for the sizes of the progenitor and its fragments.

1. Introduction

Splitting is a relatively common phenomenon among comets, even though its detection is observationally difficult, because companions are almost invariably very diffuse objects with considerable short-term brightness variations. Comet Shoemaker-Levy 9's behavior was generally less erratic than that of an average split comet, which may have in part been due to a major role of large-sized dust. The breakup products that contributed most significantly to the comet's total brightness are referred to below as *components*, or, because of their diffuse appearance, as *condensations*, both common terms of cometary phenomenology. The terms *nuclei* and *fragments* are instead reserved for genuine solid bodies of substantial dimensions ($\gtrsim 1$ km across) that were "hidden" in the condensations. A condensation may contain many fragments or nuclei, besides large amounts of material of subkilometer-sized and smaller particulates, the entire population of which is characterized by a certain size distribution function.

A total of 21 split comets had been documented in the literature by 1980 (for a review, see Sekanina 1982) and ten additional ones have been reported since. Of these recent entries, fully seven are or were short-period comets (79P/du Toit-Hartley, 108P/Ciffré, 101P/Chernykh, D/Shoemaker-Levy 9, P/Machholz 2, 511P/Arrington, and the parent of 42P/Neujmin 3 and 53P/Van Biesbroeck); two are (or were) "old" comets (of which Takamizawa-Levy 1994 XIII = C/1994 G1 is one, while the breakup products of the other were discovered as two separate objects, Levy 1987 XXX = C/1988 F1 and Shoemaker-Holt 1988 III = C/1988 J1, orbiting the Sun in virtually identical paths with a period of $\sim 14,000$ years and passing through perihelion $2\frac{1}{2}$ months apart); and one is a "new" comet, from the Oort cloud (Wilson 1987 VII = C/1986 P1). Shoemaker-Levy 9 was unique among all the split comets in that the maximum number of condensations observed *at the same time* was by far the largest. It is shown below, however, that without the italicized qualification the statement would not be valid.

Comet Shoemaker-Levy 9 is one among only a few multiple comets that are known to have fragmented due primarily - if not entirely -- to the action of tidal forces during their extremely close encounters with Jupiter or the Sun. Besides Shoemaker-Levy 9, direct evidence exists for 16P/Brooks 2, which missed Jupiter by one planet's radius above the cloud tops in 1886; and for two or three members of the sungrazing comet group (1882 II = C/1882 R1, Ikeya-Seki 1965 VIII = C/1965 S1, possibly also Pereyra

1963 V = C/1963 R1), whose perihelia were located within $\frac{2}{3}$ the Sun's radius above the photosphere. For other split comets, the nature of the disruption mechanism is not fully understood, although jettisoning of pancake-shaped fragments of an insulating mantle from the nuclear surface by stresses, built up unevenly beneath it, is consistent with the evidence suggesting that these comets 'peel off' rather than break up (Sekanina 1982).

2. The number of condensations

The detected number of Shoemaker-Levy 9's condensations depended not only on the imaging circumstances and the instrument used, but also on the time of observation, because some of the condensations disappeared with time while others began to develop companions of their own. Accounts of high-resolution observations indicate that no more than 22 condensations were detected *at a time*. On the other hand, the combined number of condensations reported on visually inspected images obtained at various *times* appears, collectively, to total 25. This is short of the record held by the progenitor of the group of sungrazing comets, from which all the observed members were found by Marsden (1989) to derive. The known sungrazers represent at least three generations of fragmentation products and include: (i) four members discovered between 1843 and 1887, one of which (1882 II) was observed after perihelion to have at least five components and another (1887 I = C/1887 B1) always appeared as a headless object (Kreutz 1888); (ii) four members discovered between 1945 and 1970; (iii) six members detected with a coronagraph onboard the SOLWIND spacecraft, between 1979 and 1984; (iv) 10 members detected with a coronagraph onboard the Solar Maximum Mission spacecraft between 1987 and 1989; and (v) any possible precursor objects, of which an uncertain orbit exists for one (the comet of 1668 = C/1668 E1) and very little information on two more (the comets of 1106 and 371 BC). Excluding the dubious companion to 1963 V, a few unlikely candidates in the 17th through 19th centuries (for an overview, see Marsden 1967), and the comets of 1106 and 371 BC, one still finds a total of 29 comets and companions—a number that moderately exceeds the 25 condensations of Shoemaker-Levy 9 observed over a period of nearly 150 years. However, if this system of comet parentage is accepted, the number of catalogued split comets should be decreased by one, because 1882 II and 1965 VIII would not then be listed as separate entries. On the other hand, if only first-generation products of an object should be counted, the number of sungrazers would drop, but so would the number of condensations of comet Shoemaker-Levy 9, as discussed in some detail in Sec. 4.3.

3. Appearance of comet Shoemaker-Levy 9

The comet's condensations were all aligned in an essentially rectilinear configuration, which extended almost perfectly along a great circle of the projected orbit and whose appearance has often been fittingly compared to a *string of pearls*. In the technical literature, the collection of the condensations is usually referred to as the *nuclear train* or just the *train*. Even though the condensations were the most prominent features contributing substantially to the total brightness, significant amounts of material were also situated in between them, along the train's entire length.

The comet further exhibited three other kinds of morphological features. Extending from the train on either side were *trails* or wings, of which the east-northeastern one appeared to be slightly inclined relative to the train. Subtending a relatively small angle with the train and pointing generally to the west was a set of straight, narrow tails, whose roots coincided with the distinct condensations in the train. These parallel tails

were immersed in, and on low-resolution images gradually blended with, an enormous, completely structureless sector of material, which was stretching to the north of its sharp boundary delineated by the nuclear train and the two trails,

3.1. The nuclear train

To describe the train's structure in detail, two notations were proposed to identify the condensations. The system introduced by Sekanina *et al.* (1994; hereafter referred to as Paper 1) has been employed, especially after the impacts, almost universally: the easternmost condensation, the first to crash, was named A; the westernmost, which crashed the last, W. The letters 1 and O were excluded to avoid any confusion with the symbols used for the respective digits. The relationship between this notation and Jewitt *et al.*'s (1993) system, which numbers the condensations, is: $A \equiv 21, B \equiv 20, \dots, W \equiv 1$.

The train's length, defined by the projected distance between the condensations A and W, continuously grew with time, from ~ 50 arcsec shortly after discovery in late March to almost 70 arcsec by mid-July of 1993, to more than 2 arcmin by the beginning of 1994, to about 5.5 arcmin by early May, and to some 10 arcmin, equivalent to a projected distance of more than 2 million km, by early July 1994. The train's enormous extent was reflected in the time span of 5.5 days between the first and the last impacts: July 16.84 UT for A and July 22.34 UT for W (Chodas & Yeomans 1994).

The train's orientation varied relatively insignificantly during the period of more than one year between discovery and collision. The position angle, measured in the direction from A to W, was within 1° of 256° between late March and mid-July 1993, decreasing to 245° by the beginning of 1994, reaching a minimum of 241° in early March, a maximum of 244° at the beginning of June, and decreasing again, at an accelerating rate, to $\sim 240^\circ$ by mid-July 1994.

A detailed analysis of the alignment of the individual condensations showed that five of them: B, J, M, P (later resolved into $1'$ and $1''$; see Sec. 3.2), and J- exhibited small but detectable off-train deviations on high-resolution images as early as March–July 1993, during the first four months after discovery (Table 8 of Paper 1). From a comparison of the 1993 pre- and post-conjunction observations, it became apparent that this group of “anomalous” condensations also included F. And more recently, with the use of a large number of 1994 observations, this category of condensations grew further, now also encompassing N, Q₂ (see Sec. 3.2), U, and V. Thus, ten of the observed condensations were found to deviate noticeably from the train “proper”. To this date it is not clear whether some other condensations, in particular C and/or D, should likewise be classified as members of this group.

3.2. Physical evolution of the train

Two of the condensations, J and M, had only been detected by Jewitt *et al.* (1993) on four occasions between late March and mid-July 1993. They are not apparent on the images taken with the Hubble Space Telescope (11 S'1') on July 1, 1993 (Weaver *et al.* 1994) and were not reported at any time during 1994. An unpublished account of a possible detection of J on the comet's image taken at Mauna Kea on December 14, 1993 does not appear to be correct.

The first signs of impending dramatic changes in the appearance of the train became evident on the July, 1993 images obtained with the HST (Weaver *et al.* 1994). While the components J and M vanished, the condensation Q, the brightest at the time, appeared to have a faint, diffuse companion some 0.3 arcsec away at a position angle of $\sim 30^\circ$. At the location of the condensation $1'$ two very diffuse nebulosities can be seen, less than 1 arcsec apart and aligned approximately with the train. The condensation L may also

have exhibited a companion nebulosity to the north. The spatial brightness distribution in the condensations was reported by Weaver *et al.* to be significantly flatter than the inverse first power of distance from the center, with no molecular emissions in the spectral region between 2220 and 3280 Å.

By late January 1994, the time of the next HST observation (Weaver *et al.* 1995), the 1' - Q region had developed considerably. The condensation Q was manifestly broken into two, a brighter Q_1 and a fainter Q_2 , 1.2 arcsec apart and the fainter to the north-northwest of the brighter. The condensation 1' also consisted of two widely separated nebulosities. The fainter and poorly condensed component, P_1 , was 4.2 arcsec from Q_1 and almost exactly to the north, while the brighter, $1'_2$, was 5.0 arcsec from Q_1 in the north-northeastern direction. The separation of P_1 from $1'_2$ was 2.2 arcsec, the former nearly to the west of the latter. Both components looked elongated: P_1 very distinctly to the west-northwest, in the direction of the tail; P_2 less noticeably to the southwest. Another significant development was the issuance, in the southward direction, of a bright "spur" from the condensation S (Weaver 1994). The spatial distribution in the condensations became steeper than the inverse first power of distance. The appearance of the nuclear train, except for the condensation W, is shown in Fig. 1.

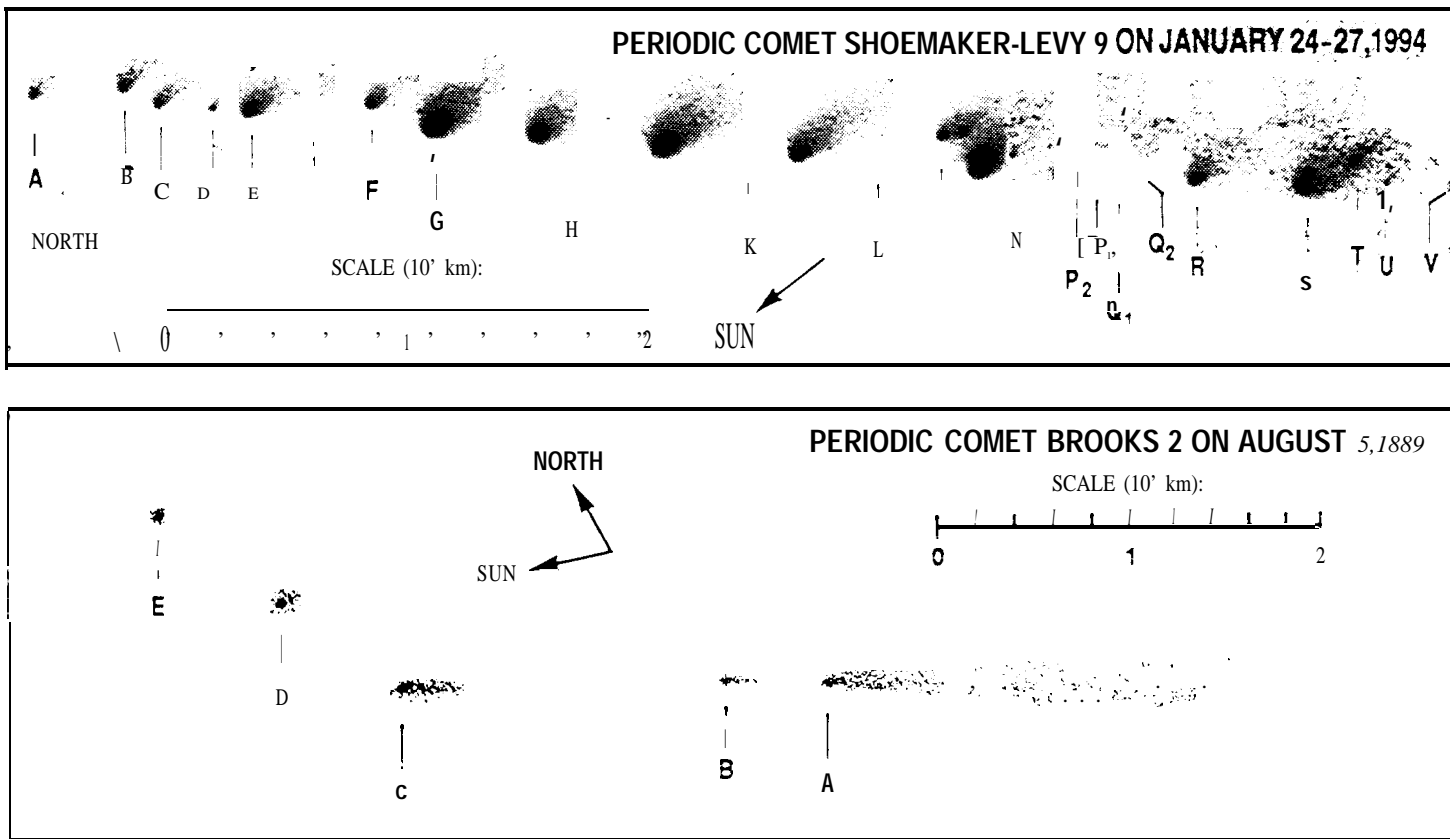
Further morphological changes were noticed on the HST images of the comet taken on March 29-30, 1994. The condensation $1'_2$ had become double, the fainter component appearing rather diffuse, and the spur of S had grown fainter (Weaver 1994; Weaver *et al.* 1995). While most condensations were still sharply defined, the components $1'_1$ and T were barely discernible as virtually uncondensed masses of material. Again, no molecular emissions were detected in the 2220-3280 Å region.

The HST monitoring of the comet continued throughout the months of May-July 1994, one of the highlights of this period being the spectral detection of a strong outburst of Mg^+ on July 14, followed by a major increase in the continuum about 18 minutes later (Weaver *et al.* 1995). The absence of any neutral molecular emissions in the spectrum between 2220 and 3280 Å was again confirmed. The images show that the central regions of the condensations, a few seconds of arc across, remained spherically symmetric until one week or so prior to impact, at which time they began to grow strikingly elongated along the direction of the train.

In the meantime, ground-based observations interrupted in late July 1993 because of the comet's approaching conjunction with the Sun--resumed in early December 1993 and continued during 1994 until impact. The condensation P_2 was observed extensively and as late as July 14 at the European Southern Observatory at La Silla and July 19 at the Mauna Kea Observatory. Ground-based observations of P_1 apparently terminated in late March. The condensation Q_2 may have been sighted on only a few occasions and was measured perhaps just once. On May 7, 1994 Jewitt & Trentham (1994) detected a companion to the condensation G, 5.1 arcsec to the northeast of it. The existence of this companion was confirmed on the HST images taken on May 17, by which time its separation distance increased to 5.9 arcsec (Noll & Smith 1994). On the other hand, its identity with a faint object located 4.1 arcsec to the north-northeast of G on the HST images from March 29 is highly doubtful.

3.3. *The dust trails*

Observations of the two trails are very limited, compared with the extensive amount of information available on the nuclear train. Almost all the published data refer to the early post-discovery period, late March through late May 1993. Their nearly complete list is presented in Table 2 of Paper 1. The west-southwestern trail was perfectly aligned with the nuclear train and its southern boundary appeared to be marginally sharper than



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Fig.1. Comparison of the appearance of periodic comets Shoemaker-Levy 9 and Brooks 2. *Top:* Mosaic image of the nuclear train (except for the condensation W) and the tails of Comet Shoemaker-Levy 9 taken with the Wide Field Planetary Camera 2 of the Hubble Space Telescope on January 24-27, 1994. The 20 visible condensations are identified in the commonly used notation introduced by Sekanina *et al.* (1994) and later expanded to accommodate the additional condensations. The projected linear scale at the comet and the directions of the north and the Sun are shown. (Adapted from an image provided by courtesy of H. A. Weaver and T. E. Smith, Space Telescope Science Institute.) *Bottom:* Drawing of P/Brooks 2 made by E. E. Barnard (1889) and based on his visual observation with the 91-cm equatorial of the Lick Observatory on August 5, 1889. The notation used for the five condensations is that of Barnard. The scale and the orientation of the drawing are also shown.

that of the east-northeastern trail. The two trails made an angle of 176° with each other, with an uncertainty of about $\pm 2^\circ$. No morphological features that could possibly suggest the presence of faint condensations were ever reported in either trail, but it appears that not enough effort has been made with this goal in mind. To the north, the trails blended into the structureless sector of material. From the descriptions based on 10 low-resolution images, the length of the east-northeastern branch was, on the average, 0.63 the length of the west-southwestern branch. The maximum lengths were reported by Scotti (1993) on March 30, 1993: ~ 10.4 arcmin at a position angle of 260° for the west-southwestern branch and ~ 6.2 arcmin at 75° for the east-northeastern branch, measured from the train's midpoint. Computer processed images show, however, no clear difference between the lengths of the two branches (Scotti & Metcalfe 1995). The only 1994 observations of the trails that I am aware of were reported by Lehký (1994) and by Scotti & Metcalfe (1995), both during February. The trails were fading rapidly with time and their expansion was consistent, according to Scotti & Metcalfe, with the assumption of no evaporation and no further production of dust material.

3.4. *The tails*

The tails associated with the condensations were observed virtually at all times between discovery and collision. Their orientations and lengths derived from the comet's ground-based images taken in the early period after discovery were summarized in Table 2 of Paper 1. The tails were reported to point at this time at the position angles between 280° and 300° , making an angle of $\sim 30^\circ$ with the nuclear train. Their lengths, depending on observing conditions and on the employed telescope, the exposure time, and the spectral window, were found to be up to ~ 80 arcsec. Additional tail observations were made by Scotti & Metcalfe (1995) in both 1993 and 1994 and by R. H. West *et al.* (1995) shortly before impact. These results are discussed in Sec. 4.4.

The tails are displayed prominently on most of the HST images obtained in 1994, an example of which, from late January, is reproduced in Fig. 1. Each condensation had its own tail, whose length and degree of prominence clearly correlated with the "parent" condensation's brightness. The tails of the major condensations, such as G or K, are seen to have extended at this time all the way to the edge of the field and their lengths must have greatly exceeded 25 arcsec, or 100,000 km in projection onto the sky plane.

The apparent breadth a few seconds of arc from the condensation is estimated at ~ 6 – 7 arcsec for the brightest tails, but only at ~ 2 arcsec or so for the fainter ones, corresponding to projected linear widths of 8000 to 25,000 km. There is evidence that the tails of some of the condensations (such as F, H, and S) broadened more significantly with distance from the train than did the tails of other condensations (such as C, K, and L). There also is an indication that the angle between the directions of the train and the tails might have been getting smaller with time.

3.5. *Comparison with other tidally split comets*

Even though the appearance of comet Shoemaker-Levy 9 was unquestionably unique among observed comets, certain similarities, however remote, can be found with two other tidally disrupted comets, P/Brooks 2 (1889 V) and the sungrazer 188211. The recognition of such similarities is of the essence in the context of establishing the diagnostics of tidally split objects and their observable characteristics.

During its approach to Jupiter on July 21, 1886, the jovian orbit of P/Brooks 2 was slightly hyperbolic (Sekanina & Yeomans 1985) and the comet's post-encounter orbital evolution was very different, from that of Shoemaker-Levy 9. After passing two planet's radii from the center of Jupiter, P/Brooks 2 settled in a new heliocentric orbit, whose

perihelion distance was 1.95 AU. The comet was discovered about three years later and was 1.16 AU from the Earth and 2.01 AU from the Sun and approaching the perihelion, when Barnard (1889) made the object's drawing on August 5, 1889, shown in Fig. 1. Two of the morphological features recognized in comet Shoemaker-Levy 9 are apparent on this drawing: (i) the nuclear train, consisting of the condensations A, B, and C and (ii) the tails, which in this case were aligned with the train. The condensations D and E, either of which was seen on only two occasions, represent a pair of "anomalous", off-train components analogous to Shoemaker-Levy 9's condensations B, F, h', etc. in addition, on one night Barnard (1889, 1890) detected four other faint companions to the south of the train and more distant from A than was E, but all of them remained unconfirmed, as did a companion reported by Renz (1889) on another day. Barnard (1890) suspected that at least some of these objects may have in fact been faint, unrecorded nebulae.

There was no evidence for wings extending from the condensations in either direction or for a sector of diffuse material spreading to either side of the train. However, Weiss (1889) reported the detection of a nebulous sheath encompassing the condensations A and B, while Barnard (1890) remarked on the absence of any such nebulosity during his observations on the same dates.

Although the relatively straightforward, empirically inferred parallelism between some of the morphological properties of comets Shoemaker-Levy 9 and Brooks 2 is found to be rather encouraging and appealing, the results of dynamical calculations suggest that the situation is more complicated and that there are even fewer similarities between the two comets than one is at first sight led to believe.

The nuclear region of the sungrazing comet 18821 I was observed to consist of at least five condensations after perihelion. They lined up in the orbital plane in a direction that, after correcting for effects of foreshortening, was lagging the Sun-comet line by more than 20° in the early post-perihelion period, but gradually less with time, until the two directions coincided some 5-6 months later, at the time of the final observations (Kreutz 1888). The brightness of the individual components varied with time, but the second and the third condensations from the train's sunward end were consistently the most prominent ones. An elongated nebulous sheath of material was enclosing the entire train. When last measured, about 150 days after perihelion, the sheath was almost 3 arcmin long, which is equivalent to a projected extent of more than 300,000 km. It is conceivable that the far regions of the sheath would have eventually evolved into wings similar to those displayed by comet Shoemaker-Levy 9, if they were sufficiently bright to have remained under observation still longer.

4. Implications for modelling comet Shoemaker-Levy 9

Before turning to the discussion of the various models proposed for comet Shoemaker-Levy 9, I list a few critical issues that represent excellent test criteria and are therefore to be addressed first. The merit of a paradigm depends primarily on the degree of its conformity with observations used in the course of its formulation, but also on the plausibility of the assumptions employed, and obviously very much on the success of any verifiable predictions that it might offer.

4.1. Morphological test criteria

From the descriptions of the comet's appearance in Sec. 3, two criteria are identified for testing a model: (i) it should explain quantitatively the four classes of morphological features detected (the nuclear train, trails, tails, and the sector of material) and their evolution and properties; and (ii) it should be conceptually consistent with

unambiguous, model-independent conclusions based on direct observational evidence. Each model should also be judged in a broader context, in such terms as the object's implied long-term dynamical stability, the plausibility of postulated properties, and the paradigm's compatibility with current views on the physical behavior of comets.

The aspects of the problem that are considered the most significant are individually discussed below. The first point to make is that the four classes of dust features should be viewed as different manifestations of the same process and as integral products of an initially single object. If either of these premises should be relinquished, one may as well abandon altogether any attempt to formulate a physical model for comet Shoemaker-Levy 9. Once these premises are accepted, however, any model based on the interpretation of only some of the morphological features (such as the nuclear train) should at best be considered incomplete and tentative, the judgment of its merit should be postponed subject to further testing, and all the conclusions to which it leads should be viewed with caution and skepticism.

The second point to make is that the observed morphology of the nuclear train of comet Shoemaker-Levy 9 offers most information and its analysis should unquestionably be the top priority in modelling efforts. Some of the train's properties are **diagnostically so critical** that they deserve special attention.

4.2. *The train's orientation*

Temporal variations in the train's orientation are among the dynamical characteristics of comet Shoemaker-Levy 9 that have been determined with very high accuracy and are of fundamental importance from the standpoint of modelling. The dependence of the position angle of the nuclear train on the conditions at the time of tidal disruption was investigated in Paper 1. The orbital calculations showed conclusively that for a given trajectory of the comet and a fixed time of breakup, no measurable effect on the train's orientation could be generated by variations, within physically meaningful ranges, in the initial radial distances of the fragments from Jupiter (which represent the dimensions of the parent nucleus) or in their orbital velocities (which simulate any effects in the rotational and/or translational momentum), or some combination thereof. The only parameter that demonstrably affects the train orientation in a systematic manner is the model-independent *time of dynamical separation*, also called the *effective time of breakup*.

In practice, the train's position angles derived from astrometric observations were found to depend slightly, but measurably, on the selection of the condensations. For the sake of uniformity, it was necessary to select a "standard" set of condensations. Since the origin of the group of anomalous condensations (B, F, J, M, N, etc.) was suspect, its members were the first to be excluded from any such standard set. The selection was essentially dictated by a balance between two somewhat contradictory requirements: (i) by the need to employ the largest possible number of observations and (ii) by a condition that the position angles calculated from the standard set be representative of the "intrinsic" orientation of the train as a whole. Since most observers measured only brighter condensations, the first point implies the need to employ as few condensations as possible. By contrast, the second point requires a large number. After much experimentation, the standard set was defined in Paper 1 by eight condensations—E, G, H, K, L, Q (later Q₁), S, and W. Comparisons with other sets showed that, except when the anomalous condensations were much involved, the position angles differed at most by a few hundredths of a degree. This is only a small fraction of the typical uncertainty involved in the position-angle determinations, which was about $\pm 0^\circ.1$ for high-resolution images (telescopes of ~ 1.5 -meter aperture or larger) and some $\pm 0^\circ.3$ or so for images of lower resolution (telescopes of ~ 1 -meter aperture or smaller).

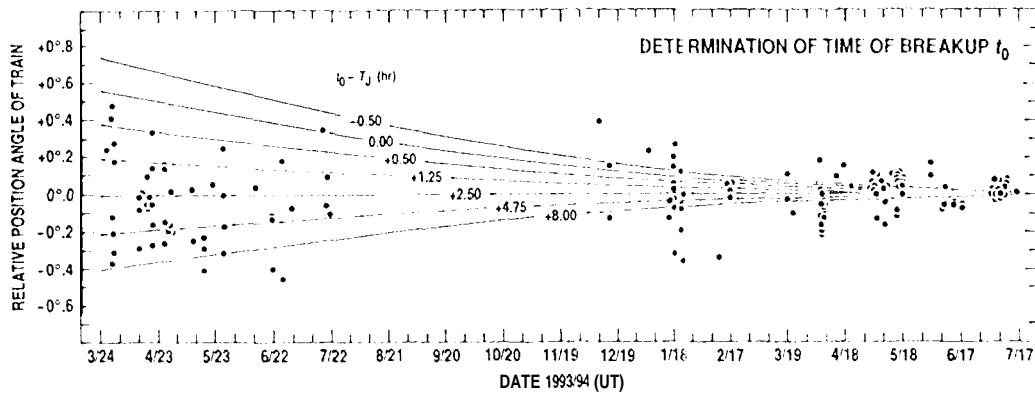


Fig. 2. The temporal distribution of residuals of the nuclear train's position angle as a function of the assumed effective time of tidal disruption, t_0 . The dots represent the 144 data points, determined by fitting astrometric observations of the standard set's eight collimated stars E through W. The curves show the variations in the calculated position angle for seven different effective times of breakup measured relative to the time of perijove, $T_J = 1992 \text{ July } 7.860364 \text{ TDB}$. For the optimized solution, $t_0 - T_J = 2.5$ hours, the calculated variations are represented by a straight line. (After Sekanina *et al.* 1995.)

Although relatively subtle, the deviations of the nuclear train orientation from the values predicted for perijove were found in Paper 1 to be sufficiently pronounced that the *effective time of breakup*, t_0 , could be determined, with an estimated error of ± 0.5 hour or so, from observations made primarily in the early post-discovery period of time. The time t_0 , which describes the completion of a post-breakup collisional redistribution of the debris rather than the initiation of tidal fracture, was calculated in Paper 1 to equal 2.2 hours after perijove, based on a total of 42 astrometric positions from 1993. A new result based on the recently expanded database, including all 144 relevant observations from 1993-1994 (Sekanina *et al.* 1995), essentially confirms the solution derived from the smaller sample; the statistically best estimate is now 2.5 hours, again with an estimated error of ± 0.5 hour. The distribution of the residuals in Fig. 2 shows that the 1994 observations, while entirely consistent with the 1993 ones, fail to improve the solution significantly because of a dramatic decrease in the sensitivity. The detailed interpretation of the effective breakup time is an issue that each model is to settle within its own framework. I will return to this problem in Sec. 5.

4.3. Secondary fragmentation

The next fundamental issue is that of the origin and the nature of the off-train, anomalous condensations. This point, too, was addressed in Paper 1 on the example of the motion of the component 1' relative to Q. The 12 relative positions between late March 1993 and mid-January 1994 could be satisfied with a mean residual of ± 0.28 arcsec, if 1' separated from Q in mid-November 1992 (with an uncertainty of a few weeks) at a relative velocity of 0.9 m/s. Evidence for similar events of *secondary fragmentation* became ubiquitous during 1994. Two examples are reproduced in Figs. 3 and 4, both based on the results of a work in progress (Sekanina *et al.* 1995). Figure 3 displays an updated solution to the motion of 1' relative to Q, which satisfies 74 observations between March 27, 1993 and July 19, 1994 with a mean residual of ± 0.29 arcsec. The breakup was found to have occurred on 1992 Dec. 29 ± 9 days with a separation velocity of 1.144 ± 0.08 m/s. Figure 4 displays the motion of Q_2 relative to Q_1 , based on very accurate measurements from the HST images. The eight positions cover the period of time from July 1, 1993,

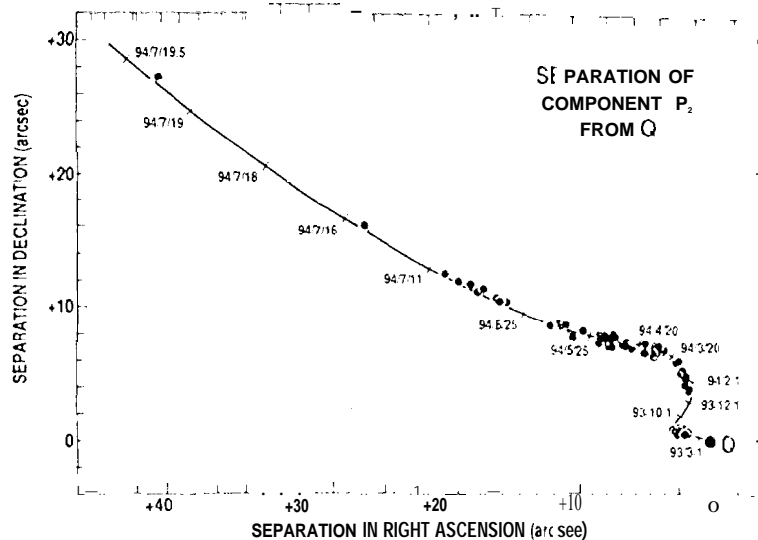


Fig. 3. Projected motion of the component P₂ relative to Q, based on 74 observations between March 27, 1993 and July 19, 1994 and interpreted as due to a splitting of the two condensations on Dec. 29, 1992 with a relative velocity of 1.14 m/s. The dots are the observations and the curve shows the optimized dynamical solution. (After Sekanina et al. 1995.)

when the two components were just 0.3 arcsec apart, to July 20, 1994. The solution, leaving a mean residual of ± 0.029 arcsec (!), yields 1993 Apr. 12 ± 8 days for the date of splitting and 0.32 ± 0.02 m/s for the separation velocity.

The fact that the comet's fragmentation continued as a sequence of discrete events for a considerable time after the 1992 grazing encounter with Jupiter has enormous ramifications. First of all, secondary fragmentation was positively nontidal in nature. Next, for all practical purposes it is certain that *all* of the off-train condensations were products of this process, so that the number of major components split off from the parent comet by tidal fracture was not 21, but most probably 10–12. The preliminary results also indicate no need to introduce differential accelerations in the motions of the off-train condensations, although much work still remains to be completed. The apparent absence of such accelerations lends support to *tentative* conclusions that neither effects of solar radiation pressure nor nongravitational effects have been detected, and that these condensations were neither 100SC assemblages of *small-sized* particulate material nor did they display any activity.

Secondary fragmentation will unquestionably stay in the forefront of attention for some time to come. A plausible physical model for Shoemaker–Levy 9 must account for this sequence of discrete events, most of which appear to have taken place between early July 1992 and the beginning of 1993, when the nuclear train was receding from Jupiter, and also explain the observed relative velocities involved, of up to at least 1 m/s.

4.4. Tail orientation and morphology: Relation to the problem of activity

The problem of Shoemaker–Levy 9's outgassing activity, especially after discovery, has been a hotly debated issue. With the exception of the brief appearance of Mg^+ shortly before impact (as already mentioned in SCc. 3.2), no emission was ever detected spectroscopically. The unsuccessful search for the hydroxyl radical with the HST's Faint Object Spectrograph and from the ground yielded a 3σ upper limit on the water production rate of 30 to 60 kg/s (Weaver et al. 1995; quoted here is the range of corrected values).

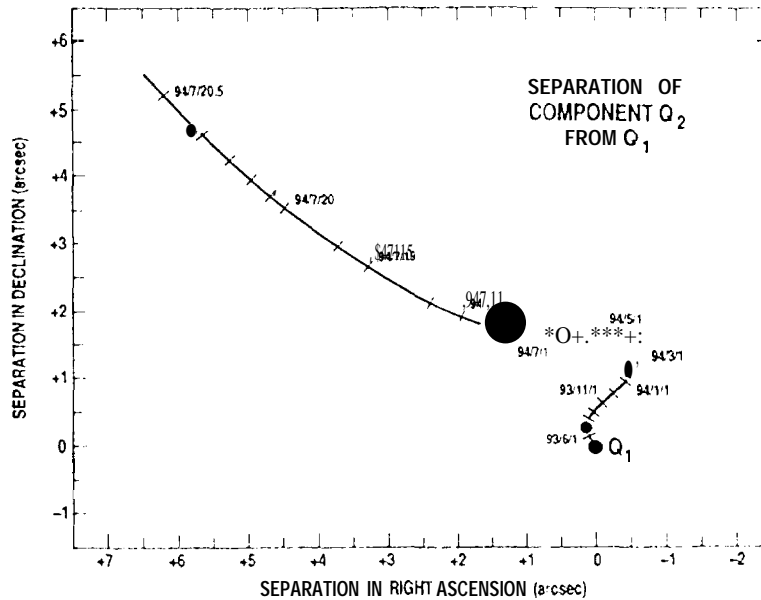


Fig. 4. Projected motion of the component Q_2 relative to Q_1 , based on eight 11 S'T observations made between July 1, 1993 and July 20, 1994 and interpreted to result from a splitting of the two condensations 011 Apr. 12, 1993 with a relative velocity of 0.32 m/s. The dots are the observations and the curve shows the optimized dynamical solution. (After Sekanina *et al.* 1995.)

Indirect information on the object's possible activity is provided by the orientation and morphology of the dust tails. It was stated in Paper 1 that the orientation of the tails observed in March 1993, shortly after the comet's discovery, essentially supports the conclusion that they consisted of particulate material that had been released during the tidal breakup in early July 1992 and subsequently subjected to effects of solar radiation pressure. The results of R.M. West *et al.*'s (1995) careful study of the tails of the fragments G and K in the period of July 1-15, 1994 are also generally consistent with this conclusion. The new preliminary results of our work (Sekanina *et al.* 1995), which is still continuing, indicate that, using an updated set of orbital elements for the fragments, we have apparently detected small but systematic deviations of the tails' reported position angles from the tidal-breakup synchrone. The dependence of the tail orientation on the time of particle release is plotted in Fig. 5. The observed tail orientations are from four sources: (i) most of the data in March 1993 are from Table 2 of Paper 1; (ii) the majority of the points before July 1994 are preliminary values for the fragment G by Scotti & Metcalfe (1995), with an estimated uncertainty of several degrees; (iii) two points are the author's estimates on available HST prints (for six fragments in each case); and (iv) the points in July 1994 are averages of R.M. West *et al.*'s (1995) results for the fragments G and K at 15,000 km from the condensation. It is evident from Fig. 5 that the synchrones corresponding to times of release in September–November 1992 are formally more consistent with the observed orientations than the synchrone of early July 1992. Because of uncertainties involved in the measured position angles and the poor resolution due to the "rowding" of the synchronies, all one can conclude at this time is that the observed tails consisted of dust particles released most probably during the period of time between early July and the end of 1992. Available evidence does not make it possible to decide (i) whether the release of the particulates was continuous or proceeded

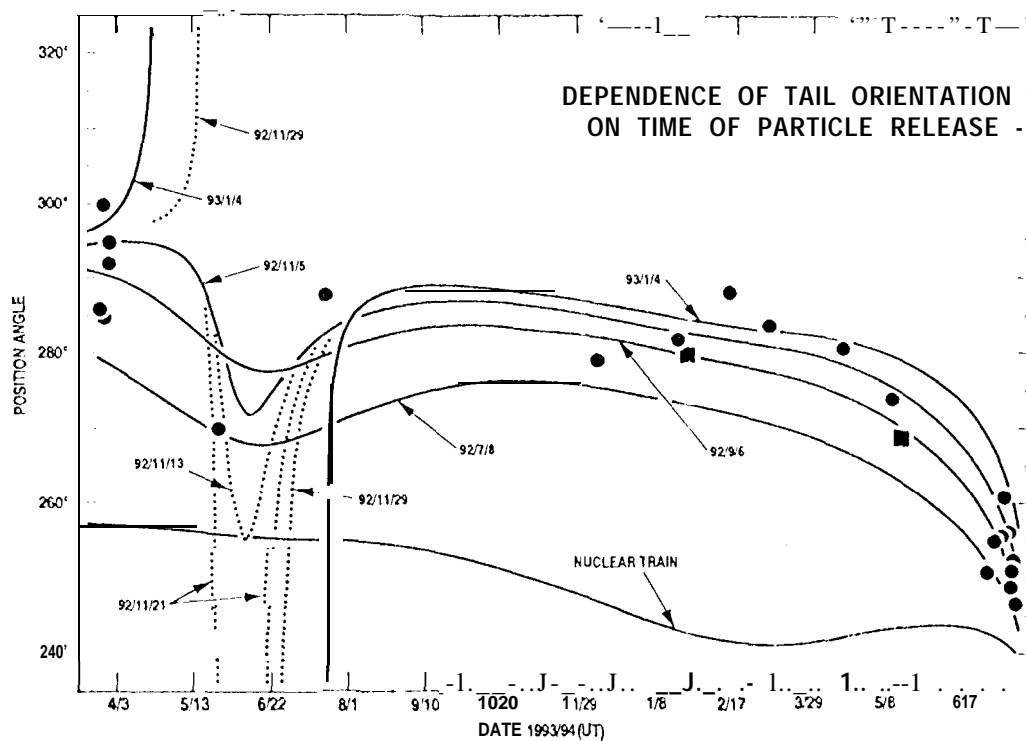


Fig. 5. The tail orientation as a function of the assumed time of release of particulate material. '1' deposition angles measured on ground-based images are plotted as circles; those estimated by the author from two HST prints, as squares. Most of the March 1993 data are from '1'able 2 of Paper 1; the majority of the points before July 1994 are preliminary values for the fragment G by Scotti & Metcalfe (1995); and those from July 1994 are averages of R. M. West *et al.* (1995) results for the fragments G and K at 15,000 km from the condensation. The synchrotrons for particles released in mid- through late November 1992 became nearly aligned with the comet-Earth line during May and June 1993, resulting in a rapid variation in the position angle (dotted curves). The nuclear-train orientation is plotted for comparison. (After Sekanina *et al.* 1995.)

in a sequence of discrete events and (ii) whether or not it was outgassing-driven. From the temporal coincidence it is tempting to associate the tail formation with both the tidal breakup and the events of secondary fragmentation. However, unless more is learnt about Shoemaker-Levy 9's tails in the future, the proposed relationship with the secondary-fragmentation events will necessarily remain speculative.

It was argued in Paper 1 that if the fragments were active, they would have displayed tails to the east-southeast from the condensations during certain periods of time (spanning many months), contrary to the observations. In order to address a counterargument (Weaver *et al.* 1995) that such tails may not have been detectable, if the dust production rates were very low, it clearly is desirable to obtain at least crude quantitative estimates for critical dust production rates. Although this issue is not here investigated systematically, two examples shown below are sufficient to illustrate approximate limits that such considerations imply. In both examples the particle size distribution function is assumed to vary inversely as the fourth power of the particle size—a reasonable approximation supported by results on a number of comets, the visual geometric albedo of the dust is taken to be equal to 0.04, and the total dust production rate is understood to refer to particles whose sizes range from 0.1 μm to 1 cm. For the assumed size distribution, the

results are relatively insensitive to the choice of the size limits; increasing, for example, the upper limit from 1 cm to 1 m would increase the production rate by a factor of only 1.4. In the first of the two cases, I assume dust particles ejected in early January 1993. In late May 1993 some of these ejecta would be located in a tail about 15 arcsec away from the parent fragment and at a position angle of $\sim 110^\circ$. If the tail detection on ground-based images requires, conservatively, a surface brightness of, say, $\sim 24 \text{ mag/arcsec}^2$, the limiting dust production rate is $\sim 2 \text{ kg/s}$, more than an order of magnitude lower than the quoted upper limit on the water production rate. In the second case, I assume ejections near March 20, 1994. On the comet's image taken with the HST on May 17, 1994 (reproduced by Weaver *et al.* 1995 in their Fig. 1) a tail consisting of these ejecta should be at a position angle of $\sim 103^\circ$. If at $\sim 5 \text{ arcsec}$ from the parent fragment this tail should have a surface brightness of $25.5 \text{ mag/arcsec}^2$, which is above the 11 S1's instrumental noise and therefore easily detectable, the limiting dust production rate would be merely 0.2 kg/s , yet another order of magnitude lower.

It is obvious that the observed tails must have consisted of dust released exclusively, or almost exclusively, in the second half of 1992. This conclusion sets tight constraints on particle sizes and velocities. The dynamical modelling indicates that the solar radiation pressure accelerations on dust grains in the tails were extremely low. For example, on the July 1994 images taken by R.M. West *et al.* (1995) the typical acceleration ratio of radiation pressure to solar attraction on particulates located 15,000 km from the parent fragment amounted to 0.00005, if they were released in early July 1992, or to 0.00020, if in late 1992. These are pebble-sized objects, with typical diameters between 1 and 10 cm, depending on their bulk density. The width of the tails is determined by limits to the particle velocity distribution in the plane normal to the orbital motion; from the projected linear widths in late January 1994 (Sec. 3.4) and the age of the particulates at the time (~ 13 – 19 months), one finds characteristic velocities in the range from 0.1 to 0.4 m/s, comparable with the separation velocities of the products of secondary fragmentation (Sec. 4.3). And since each tail is clearly an outgrowth of its parent condensation, particles in the latter must have had even larger sizes and lower velocities.

5. Models for the splitting of comet Shoemaker-Levy 9

All published models for comet Shoemaker-Levy 9 are based on the assumption that the Jovian tidal forces were either entirely, or primarily, responsible for the comet's breakup. This notion is supported by the orbital calculations, which show that the spatial positions of the various condensations, extrapolated from their absolute astrometric observations in 1993–1994 back in time, essentially coincided with one another at the time of closest approach to Jupiter on 7 July 1992 (Yeomans & Collins 1994), the least satisfactory correspondence being yielded by the off-train components.

5.1. Classification of the models and a historical perspective

The various models differ from one another in several respects. The critical discriminants are: (i) the gross nucleus structure and morphology of the progenitor comet and (ii) the role of particle-particle collisions. The first discriminant divides the existing models of the parent nucleus into two groups: either a strengthless "rubble pile", an agglomerate of smaller building blocks of material held together *entirely* by self-gravity; or a discrete mass of solids—whether or not of aggregate structure—possessing a definite cohesive strength. The second discriminant separates the models that account for effects of collisions accompanying the breakup from the models that treat the problem as that of a collisionless process.

The wide range of nuclear morphology introduced in modelling Shoemaker-Levy 9's nucleus is reminiscent of an old controversy between the icy *conglomerate* nucleus of Whipple (1950, 1951) and the *sand bank* model, which had kept comet experts busy for decades and which was thought—prematurely, as it now appears—to have been settled in favor of Whipple's concept by the images of Halley's nucleus returned by the Giotto and Vega spacecraft. As pointed out by Whipple (1961, 1963), the sand bank paradigm has been around, in one form or another, for a century or so. Its extreme variation—a diffuse, 100SC swarm of particles—was advocated by Lyttleton (1953), but in other versions the cometary nucleus was envisaged as a much more compact agglomerate. For example, Vorontsov-Velyaminov (1946) maintained that the nucleus of Halley's comet is ~ 30 km in diameter and consists of a cluster of meteoric blocks, each ~ 150 meters across, which are nearly in contact. Schatzman (1953) concluded that a compact sand bank assemblage could collapse under certain circumstances, if protected from dispersive forces, but he cautioned that in relevant scenarios the process might be 100 slow. Whipple (1961, 1963) showed that the compact sand bank model encounters most of the difficulties of the diffuse model and pointed out that gravitational coherence alone is unlikely to keep the nucleus intact over extended periods of time. While one may argue that comet Shoemaker-Levy 9 is an exception to the rule, an *ad hoc* postulate of this kind is questionable and should be viewed with skepticism.

5.2. Strengthless agglomerate models: The pros and cons

At least two models describe the nucleus of comet Shoemaker-Levy 9 as a strengthless agglomerate of subkilometer-sized cometsimals of the *same* size (Asphaug & Benz 1994, Solem 1994). Both are concerned only with the nuclear train and the main difference between them is that only Solem's model accounts for effects of particle-particle collisions. A third model, briefly described by Rettig *et al.* (1994), is still in the process of development; in some of its versions a nonzero mechanical strength among the ~ 50 meter sized cometsimals is considered (Mumma 1995). All distances involved in these models scale with simple similarity and the results depend critically on the bulk density of the assemblage. These properties can readily be illustrated on a spherical body, whose radius is R , bulk density ρ , and gravitational pressure at its center P_c . The gravitational attraction between its two hemispheres is $\frac{1}{2}\pi R^2 P_c$, while the net tidal force from Jupiter, of radius R_0 and density ρ_0 , amounts to $\pi R^2 P_c (\rho_0/\rho) (R_0/\Delta)^3$ at a distance Δ from the planet. The necessary condition for a hemispheric separation is independent of the radius R and is given by the following expression (Aggarwal & Oberbeck 1974, Dobrovolskis 1990)

$$\frac{P}{\rho_0} \left(\frac{\Delta}{R_0} \right)^3 < 2. \quad (5.1)$$

For Shoemaker-Levy 9 one obtains $\rho < 1.1 \text{ g/cm}^3$, probably a soft limit, since the breakup is likely to have begun before perijove (see also an independent investigation by Boss 1994). A more meaningful constraint is offered by P/Brooks 2, which approached Jupiter to 2 Jovian radii, so $\rho < 0.34 \text{ g/cm}^3$ (Sekanina & Yeomans 1985).

An attractive attribute of the self-gravitating strengthless compact agglomerate models is their apparently successful simulation of the progenitor's tidal disruption into a fairly small number (between a few and two dozen or so) of discrete clumps of debris, if the bulk density of the cometsimals is confined to a relatively narrow interval of plausible values. The reason for this unexpected result is that shortly after passing through perijove the cometsimals begin to reassemble gravitationally, but because of the considerable tidal elongation of the cloud at that time, the coagulation proceeds only locally, if the bulk density ρ is, in this particular case, close to 0.5 g/cm^3 .

The fatal flaw of the proposed strengthless agglomerate models, which for all practical purposes renders them invalidated, is the fact that they motivated grossly incorrect predictions for the impact phenomena (e.g., Weissman 1994). Due to combined effects of Jupiter's tidal forces and the aerodynamic pressure and rapid heating in the Jovian atmosphere, loose assemblages of meter- to subkilometer-sized cometesimals would indeed have disintegrated into small debris at very high altitudes and we would have witnessed a cosmic fizzle. And whereas observations do provide substantial evidence (e.g., Meadows *et al.* 1995) that *some*, and possibly *much*, of each condensation's mass disintegrated high in the Jovian atmosphere, sufficiently massive fractions of 11 of the components (including all 7 of the standard set; Sec. 4.2) penetrated into the lower stratosphere, or perhaps still deeper, where they exploded and generated huge ejecta clouds, some of which were imaged with the HST (Hammel *et al.* 1995). Furthermore, for at least a short period of time before the crash of a 100SC agglomerate, observers should have witnessed each fragment's progressive *surfacting*, driven by Jupiter's gravity and following the same basic pattern that was so prominently demonstrated by the surrounding dust coma. Instead, the innermost, brightest part of the condensations remained to appear as an unresolved dot even on very high-resolution images, as illustrated by the last HST frame of Q₁ and Q₂ in Weaver *et al.*'s (1995) Fig. 2.

These arguments indicate that the Asphaug-Benz-Solem paradigm of a strengthless agglomerate of equal-sized cometesimals cannot possibly represent a realistic model for the nucleus of Shoemaker-Levy 9. To salvage a more general concept of an agglomerate nucleus, it is essential that the cometesimals be allowed to hold together by limited strength and to possess a *broad size distribution*, including a dominant object that is capable of contributing most light to the innermost portion of each condensation on the last pre-crash images and whose residual mass can survive the flight through the Jovian stratosphere. The size distribution of the cometesimals can be introduced either *ad hoc*, as an inherent attribute of the nucleus, or by invoking significant local variations in the force that binds the building blocks in the nucleus interior, in which case some parts of the nucleus have a tendency to fall apart almost spontaneously, while others are capable of resisting relatively formidable stresses. The two scenarios for achieving a size distribution of the cometesimals do not exclude each other. In any case, a cohesive agglomerate will behave as a discrete mass of some limited strength (Sec. 5.3) and its tidal disruption characteristics could not be predicted from the dynamical properties of an agglomerate model of the Asphaug-Benz-Solem type, which becomes irrelevant.

One can list additional difficulties of strengthless models. Of these, the observed events of secondary fragmentation have the most severe implications, because strengthless assemblages of the Asphaug-Benz-Solem type could not continue to break up when receding from Jupiter (Sec. 4.3). Indeed, Asphaug & Benz show that, in their model, coagulation of cometesimals by self-gravity began to prevail already several hours after perijove. Also of concern are the critical sensitivity of the strengthless agglomerate models to the comet's rotation and bulk density; doubts whether they can at all explain the observed nuclear train orientation (Sec. 4.2), an important issue not addressed in either of the two papers; an apparent contradiction in the tacit assumption that while the dynamical behavior of the assemblage is governed purely by self-gravity, the cometesimals themselves are structurally so cohesive that their strength is not even questioned; and a highly problematic long-term dynamical stability of strengthless agglomerates. All these arguments support the notion expressed by Whipple long time ago (Sec. 5.1) that gravitational coherence *alone* cannot provide the basis for a realistic model of cometary nuclei. The arguments further imply that, in terms of fundamental structural properties, Shoemaker-Levy 9 is no exception among comets.

5.3. *Models for a discrete mass of limited mechanical strength*

Tidal splitting of a discrete nucleus that possesses some, however limited, strength is governed by different conditions. As mentioned in Secs. 5.1 and 5.2, cohesion of this model nucleus, if of agglomerate structure, may vary due to unevenly strong mechanical bonds among its building blocks or due to uneven cementing of the interiors of the individual blocks) or both. Considering a self-gravitating, incompressible elastic sphere, Aggarwal & Oberbeck (1974) showed that fracture starts either at the body's center or on its surface. In general, their result can be written in a form analogous to (5.1),

$$\frac{\rho}{\rho_0} \left(\frac{\Delta}{R_0} \right)^3 < k \frac{P_c}{U}, \quad (5.2)$$

where k is a constant on the order of unity. When fracture starts at the surface, U equals T , the body's tensile strength. When it starts at the center, $U = T + P_c$. Aggarwal & Oberbeck argued that fracture is completed when the tensile strength is exceeded by the greatest principal stress both at the center and on the surface of the body. Dobrovolskis (1990) pointed out, however, that Aggarwal & Oberbeck's approach underestimated the extent of fracture because their calculation of the stress field did not account for its changes as the fissure propagates. In any case, the critical tensile strength at which the body would begin to break apart varies as the central pressure and is therefore proportional to the square of the body's size. For fixed values of ρ, ρ_0, R_0 , and A , *tidal splitting of a comet is the easier the larger its nucleus is*. The size dependence represents a fundamental difference between the behavior of strengthless agglomerates and nuclei that are at least weakly cemented.

Secondary fragmentation is one of the observed phenomena that makes the concept of discrete cometary nuclei of limited and variable strength very attractive. The fact that the products of each secondary fragmentation event appeared as discrete condensations, rather than an elongated cloud of dust, testifies to the presence of a dominant mass in each of them. And the diffuse appearance of each such component suggests that much, if not all, of its dust cloud was formed upon separation. Without these properties one would have to postulate a bimodal velocity distribution of the dust cloud in the parent condensation, an obviously flawed premise with no physical or dynamical rationale.

Events of secondary fragmentation can readily be understood in the framework of a discrete nucleus as a result of a gradual fissure propagation. Asphaug & Benz (1994) argued that a body of any realistic density could not have been broken up into ~ 21 pieces by the tidal forces, regardless of its strength. They proposed that if the comet was not a strengthless "rubble pile" to begin with, it would have to be a structurally weak aggregate shattered by impact during its inbound passage through the Jovian ring. This scenario fails to explain the breakup of P/Brooks 2 (which never approached close enough to the planet to cross the ring) and since the initial number of major fragments of comet Shoemaker-Levy 9 was just 10 to 12 (Sec. 4.3), Asphaug & Benz's objection is no longer relevant. However, their suggestion that growing cracks in a nucleus of some inherent strength may stall is of interest, paralleling somewhat our argument in Paper 1. The implications from Paper 1 are that a body of uniform strength is pure fiction and any arguments against its expected behavior are therefore unnecessary and meaningless. A crack could stall whenever it encounters a mass of greater strength during its propagation through the nucleus. As the comet rotates, the centrifugal force would assist the tides in at least some parts of the nucleus, depending on the orientation of the spin vector. Even for a nonrotating comet, the configuration of regions of highly variable strength in the nucleus interior should be changing rapidly relative to Jupiter (and its

tidal field) near perijove because of the sharply curved orbit. An obvious inference is that there should have been *large* fragments *that had survived the Jovian encounter cracked but not completely broken* and that *some of the cracks would have been extended to the point of fracture at later times* in those among the fragments that happened to have been spun up as a result of the collisions] angular momentum redistribution) in the cloud of debris.

The plausibility of the concept of discrete nuclei of limited and variable strength is also illustrated by other idiosyncrasies of the condensations of Shoemaker-Levy 9, both in interplanetary space and upon entering the Jovian atmosphere. One of these peculiarities is the gradual disappearance of a condensation, which is particularly well documented by the HST observations of P₁ (Fig. 2 of Weaver *et al.* 1995), but was obviously also experienced by J, M, and P_{2b}. Common to these condensations was apparently their extremely poor cementing throughout their interiors on such scales that no fragment of a size detectable by the HST could survive even in interplanetary space. 'his critical size at the comet's distance is about 1 km in diameter, so the gradual disappearance of these condensations does not provide a very strict limit on the maximum fragment size and on the density of lines of extreme structural weakness in these objects.

The next group includes some other off-train condensations, such as B, F, etc., which did not disintegrate during the months before their impacts but generated no detectable ejecta. Since stresses (such as rotational) acting on comets and their fragments in interplanetary space are generally lower than the tidal forces very close to Jupiter, it appears that lines of extreme structural weakness were less densely distributed in the interiors of these fragments, but that areas of high structural weakness were still sufficiently extensive for the objects to be broken tidally shortly before they entered the atmosphere (Sekanina 1993).

Finally, the on-train condensations apparently contained kilometer-sized fragments in which areas of high structural weakness were still less common, so that these fragments survived the tidal action and began to fragment precipitously only under the effects of aerodynamic pressure, which for the impact velocity of Shoemaker-Levy 9 began to exceed the tidal force at altitudes of about 300 km or so above the 1-bar level.

These groups of fragments clearly correlate with the classes introduced by Hammel *et al.* (1995) and suggest that the distribution of lines of extreme structural weakness is this classification's criterion. However, one should not think in terms of discrete categories; instead, each fragment is likely to have its own position in the hierarchy of structural strength. One observational implication is that the off-train condensations of structurally weaker fragments should have generally appeared brighter than the on-train condensations, because a greater mass fraction of the off-train condensations was contained in the debris near the lower end of the size spectrum, so they had a higher apparent cross-sectional area per unit mass. This effect was particularly well illustrated by the first two condensations to crash, A and B, as A was in fact fainter, yet apparently much more massive. Of the on-train condensations, one example of an excessively fragile fragment was Q, which over a time gave birth to perhaps as many as five secondary fragments. This condensation had long been the brightest component of the train, yet the impact of Q was a relatively disappointing event.

The high susceptibility of cometary objects to fragmentation during flight through the Earth's atmosphere has long been known from observational evidence accumulated in the field of meteor physics (e.g., McCrosky & Ceplecha 1970). In fact, fragmentation—especially discrete fragmentation events, which trigger flares or outbursts along the atmospheric path—is clearly the dominant ablation process for massive cometary impactors. Borovička & Spurný (1995) recently analyzed a photographed cometary bolide,

which morphologically represents a good analogue for the fragments of comet Shoemaker-Levy 9. The bolide's maximum brightness normalized to a distance of 100 km reached panchromatic magnitude -21.5 , its bulk density was $\sim 0.1 \text{ g/cm}^3$, and its initial (pre-atmospheric) mass $\sim 5 \text{ tons}$. Borovička & Spurný also found that along the entire luminous path the bolide's flight was only marginally decelerated by the atmosphere. The bolide became visible at an altitude of 99 km above sea level, where the dynamic pressure reached $\sim 2 \text{ mbar}$ and the atmospheric pressure was only $0.4 \text{ } \mu\text{bar}$. An equivalent altitude in the Jovian atmosphere is $\sim 380 \text{ km}$ above 1 bar. The bolide disintegrated *entirely* by the time it reached an altitude of 59 km (an equivalent Jovian altitude of $\sim 190 \text{ km}$ above 1 bar), at a dynamic pressure of $\sim 1 \text{ bar}$ and an atmospheric pressure of 0.25 mbar . Borovička & Spurný's modelling of the object's light curve shows that almost 50 percent of the initial mass was lost in the brightest flare alone, whose FWHM duration was $\sim 0.05 \text{ second}$, and that the residual mass after this event amounted to less than 1 percent of the initial mass. This outburst was observed at an altitude of 67 km, where the dynamic pressure reached $\sim 0.4 \text{ bar}$ and the atmospheric pressure was 0.08 mbar . The fragments of Shoemaker-Levy 9 were subjected to the same dynamic pressure at an altitude of $\sim 200 \text{ km}$ above 1 bar, where the atmospheric pressure was $\sim 0.15 \text{ mbar}$.

To summarize, the paradigm of a cometary nucleus that possesses a limited but variable strength avoids conceptual pitfalls of the strengthless agglomerate models. The results for the tidal breakup are no longer critically sensitive to the bulk density, for which values significantly lower than 0.5 g/cm^3 are preferred. This limit is based not on the results obtained from the strengthless agglomerate models, but from the simple application of Eq. (5.1) to P/Brooks 2. The Shoemaker-Levy 9 progenitor could have begun to break apart perhaps as early as one hour or more before perijove, especially if its nuclear dimensions were relatively large (Sec. 5.4). The interpretation of secondary fragmentation and the explanation of the dramatic differences in the behavior among the condensations both before and upon their atmospheric entry are thus logical outgrowths of the fundamental conclusion on low and highly variable strength of tidally generated fragments and their products.

5.4. *Sizes of the progenitor nucleus and its fragments*

The dimensions of the progenitor nucleus and its major fragments have been a subject of continuing controversy. A relatively soft upper limit on the progenitor's photometric cross section results from a failure to find the comet on pre-discovery exposures taken with the 100-cm Schmidt telescope at the European Southern Observatory in March 1992 (Tancredi *et al.* 1993, Tancredi & Lindgren 1994), on which the limiting magnitude for an object having the comet's motion was $B = 21.3$. Even the largest estimates for the nuclear size indicate that the comet, if inactive, would have been at least 0.5 magnitude fainter, assuming appropriate values for the albedo and the phase coefficient.

In the papers by Scotti & Melosh (1993), by Asphaug & Benz (1994), by Solem (1994), and by Chernetenko & Medvedev (1994) the effective diameter of the original nucleus was estimated at $\lesssim 2 \text{ km}$. Scotti & Melosh found 2.3 km , but they used an early orbit whose 1992 perijove distance was too large. Refined orbits yield a miss distance of less than $25,000 \text{ km}$ above the cloud tops (Yeomans & Chodas 1994), requiring a revision of Scotti & Melosh's value to 1.8 km . Asphaug & Benz, employing a recent orbit, derived an effective diameter of 1.5 km , while Solem obtained 1.8 km and Chernetenko & Medvedev, 1.1 km .

The agreement among these results is not surprising, because they all were determined from the same observed quantity---the length of the nuclear train, always interpreted as a product of radial differential perturbations by Jupiter. Only in two of the four studies

was the issue of the trails addressed at all, very briefly in either case. Asphaug & Benz's discussion was limited to an obvious remark that trails of debris could be expected on either side of the major clumps, but they offered no quantitative information. Scotti & Melosh concluded that the trails were either made up of remnants of a dust coma that the comet had possessed before its close encounter with Jupiter, or consisted of dust liberated during the breakup and subsequently perturbed by various forces. The extent of the trails was noted by these authors to correspond to a diameter of ~ 2035 times the diameter of the parent comet but they did not elaborate on the significance of this finding. The other two papers ignored the existence of the trails altogether and none of the four studies paid any attention to the system of tails or to the sector of material to the north of the train and the trails.

In the meantime, the comet's first observations by the HST, made on July 1, 1993, were analyzed by Weaver *et al.* (1994). After subtracting the light of the surrounding comae, the magnitudes of the central nuclei in the 11 brightest condensations were calculated to imply effective diameters in the range from 2.5 to 4.3 km, at an assumed geometric albedo of 0.04. Even though Weaver *et al.* remarked that the derived nuclear magnitudes may not have been entirely free from a contamination by residual dust in the employed 3×3 pixel box centered on the brightest pixel, the effect could not possibly have amounted to >3 magnitudes, nor could the albedo have been underestimated by a factor of >20 to make the results compatible with the progenitor's diameter of $\lesssim 2$ km.

Weaver *et al.* (1995) subsequently applied the same technique to the HST observations from January and March 1994, finding that the spatial brightness distribution in the condensations could not be fitted by a simple model and that there was no reliable way of deconvolving the contributions by any unresolved sources from the surrounding dust clouds. On the other hand, application of an independent deconvolution technique to the HST images from January, March, and July 1994 by Sekanina (1995) resulted in positive detections of unresolved sources in nearly all condensations under investigation. The calculated dimensions for the major fragments were found to be virtually independent of the law used to approximate the brightness distribution of the extended source (the surrounding dust cloud) and agreed closely with those derived by Weaver *et al.* (1994) from the July 1993 data.

Several other lines of evidence also suggest strongly that the original nucleus could not possibly be $\lesssim 2$ km in diameter. From their analysis of the optical depth distribution of the dark impact debris on Jupiter imaged with the HST between 1 day and 1 month after the last impact, R. A. West *et al.* (1995) concluded that the mean particle radius was between 0.2 and 0.3 μm and their total volume was equal to the sphere 1.0 km in diameter. Since these aerosol particles are believed to have represented condensates of supersaturated vapor originating from the hot gas in the rising plumes of debris, they consisted primarily--and perhaps exclusively--of the impactor's mass and, unlike in the original cometary environment, had densities close to the mineralogical densities of the involved materials. R. A. West *et al.* adopted a density of 2 g/cm^3 , which yields a total mass of $1.0 \times 10^{15} \text{ g}$ for this optically recovered mass of the refractory material and already corresponds to an effective diameter of 2.1 km for the comet's plausible bulk density of 0.2 g/cm^3 (cf. Sees. 5.2 and 5.3). There is no doubt whatsoever that this optically recovered aerosol mass represents only a fraction of the total recondensed refractory mass of the fragments, which, in turn, represents only a small fraction of the total mass delivered to Jupiter by the fragments and by the dust clouds in which the fragments were immersed before impact. Even this total delivered mass obviously does not represent the entire mass of the original comet, although the two may be comparable in magnitude.

The incompleteness of the optically recovered aerosol mass is plainly illustrated by the fact that the contributions to the dark debris from most off-trail condensations remained undetected. Besides, R. A. West *et al.* (1995) emphasize that significant nucleation requires supersaturation and that cooling below the saturation point is not a sufficient condition for the aerosol formation. They also find that, in a dense plume of debris, silicates and similar refractory materials could condense into grains larger than $10\ \mu\text{m}$ in radius, whose sedimentation times in the Jovian atmosphere are only a fraction of 1 day. Such large particles obviously could not survive in a debris imaged days or weeks after impact. Merely R. A. West *et al.*'s results are combined with Vanýsek's (1995) estimate that only ~ 1 percent of the delivered mass should have contributed to the recondensation process, one finds a total delivered cometary mass of $\sim 10^{17}$ g. And since the optically recovered aerosol mass was probably derived from the recondensed residual mass involved in the explosions in the lower stratosphere and/or the troposphere, it would not include the fraction of the original mass of the impactors that was lost by their precipitous fragmentation in the upper atmosphere prior to the explosions and may have been responsible for, or contributed to, the detected heating of the stratosphere (e.g., Lellouch *et al.* 1995, Bézard *et al.* 1995). This missing mass has remained unaccounted for, even though it may have represented a significant fraction of the initial mass of the large fragments. Finally, from observations at millimeter wavelengths, additional substantial amounts of the delivered mass were identified by Lellouch *et al.* (1995) in the form of volatile compounds, concentrated near the 0.5 mbar pressure level and probably involved in the shock chemistry. For the fragment G alone, a total mass of 10^{14} g of carbon monoxide was detected in the telescope's beam of 12 arcsec several hours after impact (revised more recently to 5×10^{14} g; Lellouch 1995). Recovery of all these impressively large amounts of mass from an original nucleus of less than 2 km in diameter would surely represent a *humpty-dumpty* feat of unrivalled proportions.

5.5. *Rotation model for the progenitor nucleus and collisional evolution of the debris*

One of the first results of the numerical experiments conducted in Paper 1 was a finding that equivalent values could be established for an initial radial separation of the fragments or for their orbital velocity increment or for various combinations of these quantities so that they yielded identical temporal variations in the nuclear train's apparent evolution (its length and orientation), a fact that can also be derived from the virial theorem. If the breakup is assumed to have occurred at closest approach, the relevant values are 1.26 km for the radial separation (that is, the nucleus diameter) and 0.17 m/s for the orbital velocity increment. Thus, the breakup of the progenitor 1.26 km in diameter represents only one of an infinite number of possible solutions, based on a number of assumptions regarding the time of the event (*exactly* at perijove) and the comet's rotation vector (no rotation or the axis aligned with the orbital velocity vector). This is such an exceptionally special case that the probability of its having actually taken place is virtually nil. The equivalence of effects due to Jovian perturbations and due to an orbital velocity impulse signifies a basic dynamical indeterminacy of the problem, which is also reflected in the major role of the comet's rotation recognized by Asphaug & Benz (1994) and by Solem (1994) and which makes the tight constraints on the parent comet's size and bulk density in these models vulnerable and suspect.

A Monte Carlo simulation of ubiquitous low-velocity particle-particle collisions, carried out in Paper 1, showed that the initial rotational velocities were rearranged into a rapidly "thermalized" distribution, characterized by a long tail of fairly high velocities (up to ~ 7 m/s) for the debris that eventually populated far regions of the trails. The period of intense particle-particle collisions was estimated to have continued for at least

a few hours, at which time the systematic forces began to dominate. The particle mass distribution of the fragments appears to have been relatively flat near the upper end of the size spectrum but steeper for pebble-sized and smaller debris. Fine dust effectively provided a temporary viscous medium for the major fragments. Dimensions of fragments populating the west-southwestern trail probably ranged from several hundred meters down to a few centimeters, the latter constraint being dictated by the absence of measurable solar radiation pressure effects. The debris in the east-northeastern trail was mostly submillimeter- and millimeter-sized. All the debris to the north of the train-trail boundary was affected by solar radiation pressure and made up of particles that were microns to several millimeters across, the size being the largest near the boundary.

To constrain the comet's bulk properties, a rotational model was formulated by us in Paper I and a search was initiated for solutions consistent with evidence on the nuclear train and the trails, while also accommodating limited information on the tails and the sector of material. The maximum dynamically plausible train and trail lengths, searched for as functions of a location on the nucleus, depend on the nuclear dimensions and the rotation vector of the parent comet, on the effective breakup time (Sec. 4.2), on the particle-mass distribution of the debris, and on the collisional-velocity enhancement factors. Although no unique solution could be derived, models for the parent comet that fitted the constraints best implied a nuclear diameter of ~ 10 km, a spin axis nearly in the jovicentric orbital plane, and a short rotation period, perhaps 7-8 hours. For a bulk density of 0.2 g/cm^3 the net tidal stress is calculated to have been 0.0038 bar at perijove, 0.0008 bar 1 hour earlier, and 0.0002 bar 2 hours earlier, comparable with the central gravitational pressure and the centrifugal stress due to rotation. It thus appears that the comet's spin assisted the tidal forces in splitting the nucleus apart.

6. Summary and conclusions

The events experienced by comet Shoemaker-Levy 9 near Jupiter in early July 1992 began with fissures propagating throughout its nucleus, about 10 km in diameter or 10^{17} g in mass at an assumed density of 0.2 g/cm^3 . The cracks were caused by tidal stresses exerted by the planet, with some assistance from the comet's rotation. Probably even before reaching perijove, the inflicted structural failures resulted in the body's gradual breakup, first into a couple of large fragments accompanied by immense amounts of small-sized debris. Because of a distribution of rotation velocities, collisions became inevitable and, together with the continuing tidal forces, contributed to further fragmentation. The collisions] velocity distribution rapidly "thermalized" and developed a long tail, populated by particulates with relative velocities of up to $\sim 7 \text{ m/s}$. Intensive collisions did not terminate until after perijove, defining the effective time of breakup (dynamical separation). The 10-12 largest fragments contained apparently close to 90 percent of the total mass of the progenitor. The largest fragment was estimated to have been at least 4 km in diameter. A mean fragment size gradually decreased from the train to the two trails, the tails, and the sector of material, which contained microscopic debris. Definite evidence for discrete events of secondary fragmentation indicates that the comet's disintegration continued long after its 1992 encounter with Jupiter. Observed effects on the unevenly susceptible fragments provide intriguing information on the complex morphology of the comet's nucleus interior. The orbital calculations offer an independent insight by showing that fragments that ended up nearer the planet at the end of the collisions] period remained so throughout the orbit until collision, while fragments with greater velocity increments in the direction of the comet's motion had larger orbital dimensions and impacted Jupiter later.

The comet's fragments of the estimated mass will have delivered a total energy of tens of millions of megatons of 'TNT' upon impact. Much of this energy was rapidly dissipated over huge volumes of the Jovian atmosphere in the early phase of each fragment's entry and only a fraction was apparently transformed into more persisting, readily detectable effects. Whereas the impact phenomena provide critical information on the nature of the fragments' interaction with the Jovian atmosphere, the comet's tidal disruption] deserves attention in a broader context, including the role of nuclear splitting in the evolution of comets. A particularly diagnostic property concerns systematic differences in fragment configurations of tidally and nontidally split objects. Whatever the mechanism(s) of nontidal breakup may be (Sec. 1), it is well known (Sekanina 1977, 1982) that the configuration of fragments is in these cases controlled primarily by differential forces acting along the direction of the radius vector. Relative to the *principal* (parent) nucleus, which is usually (but not necessarily) the brightest component, the companions are lined up approximately along the antisolar direction shortly after their separation, but rotate their positions gradually with time and end up eventually---if they are still observable---in the direction of the reverse orbital-velocity vector, that is, they follow the parent object in its heliocentric orbit. Hence, the characteristic attribute of such configurations is that the parent nucleus is always situated at the *leading end* of the fragment lineup. This dynamical evolution is of course readily predictable from considerations of the orbital angular momentum and is indeed consistent with observations of fragments of most split comets. For only three among the split comets with more than two components ever observed was the brightest condensation situated at a "wrong" location, after each of them had broken tidally in the immediate proximity of the Sun or Jupiter: the sungrazer 188211 = C/1882 RI, 16P/Brooks 2, and Shoemaker-Levy 9. This evidence shows that the fragment configurations of tidally split comets are determined primarily by the conditions at breakup and not by the differential forces that the fragments might be subjected to following their separation.

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